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Theory overview on dark matter portals

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We provide a theoretical overview on dark matter portals. We briefly discuss portal scenarios in the context of effective field theory and present various possibilities that can be tested at the LHC, including traditional mono-X searches, conventional displaced-vertex signatures, and sequential multi-displaced-vertex signatures.

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1. Introduction

The discovery of dark matter in the universe via its gravitational interaction has greatly motivated to understand its particle nature through its hypothetical non-gravitational interactions, and an enormous experimental endeavor has been devoted in the search for particle dark matter for the last few decades, mostly focusing on a well-motivated dark-matter candidate, the weakly interacting massive particle (WIMP). However, no conclusive observations of WIMP signals have been made so far, which have motivated to look for the dark matter candidates of other mass scales. Among them, MeV to sub-GeV-range light dark matter is receiving particular attention, as it can still be produced thermally and is less constrained by existing searches. Moreover, it often involves light mediators with similar mass values to be consistent with the observed dark matter abundance, embedding itself in a portal scenario.

What we know about the dark sector including dark matter from all theoretical and experimental considerations is that they are weakly or feebly interacting with the Standard model particles. Given that, one possible way of making systematic progress is to assume that the underlying explanation is sitting in a dark sector or hidden sector that is weakly coupled to the Standard Model (SM) sector. Effective field theory (EFT) approaches can then be applied in order to systematize the exploration of the couplings between the SM and a potentially highly complex dark sector:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} + \sum_{d=i+j} \frac{1}{\Lambda^{d-4}} O_i^{\rm SM} O_j^{\rm DS} \,. \quad (1)$$

Dark-sector degrees of freedom can interact with the SM particles via SM-neutral operators of dimension j constructed from dark-sector fields. The EFT framework implicitly allows scale Λ to be very large, so practically, lower-dimensional operators have received particular attention as their coupling strengths are less suppressed. There exist renormalizable operators or portals involving no high-scale parameters. They are often quoted as higgs portal, neutrino portal, and vector portal. Once higher-dimensional operators are allowed, there are many possible operators, but a specific set of dimension-5 operators is particularly interesting as they involve an axion or axion-like particle (ALP) field.

In terms of searches, we are trawling dark-sector particles in various channels and in different types of experiments including intensity, cosmic, and energy frontier experiments. As mentioned above, dark-sector couplings are small and the mass scale is unspecified. Therefore, the discovery of the dark-sector physics can be made in any of these experiments. In this article, we focus on the dark-sector searches at the LHC.

2. Dark-sector signal at the LHC

The most famous and traditional example of the dark-sector searches performed at the LHC is the channels of mono-X plus missing transverse momentum. One can interpret that dark matter is pair-produced via an exchange of portal or mediator. Once this process involves an additional radiating SM particle (e.g., j, W/Z, γ, or h), the dark-matter existence is imprinted in the total momentum imbalance between the incoming and outgoing states. So far, no significant excesses have been found in both ATLAS and CMS, and the relevant dark matter models are more stringently

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constrained (see, for example, Refs. [1, 2]). There are efforts in the search for mediators themselves. For example, ATLAS performed a dark Z' search, envisioning the situation where a SM higgs decays to a SM Z and a dark Z' both of which decay to lepton pairs [3]. CMS performed a dark photon search, imagining the process where a new heavier higgs is produced via vector boson fusion, and decays to a photon and an invisible dark photon [4]. No excesses have been reported yet in this type of searches, either.

Given the null observations of dark-sector signals at the LHC, other possibilities are being considered. In particular, non-minimal dark-sector scenarios, which assume more dark-sector species beyond dark matter, have not been extensively investigated, and related physics opportunities receive growing attention.

The simplest non-minimal dark-sector scenario is inelastic dark matter which involves a heavier dark-sector species, say χ', on top of the dark matter species χ. Under this framework, the mono-X scenario can be modified as follows. Instead of pair-production of χ, a χ' can be produced in association with χ via an exchange of portal particle, for example, dark photon A'. By construction, χ' decays back to χ and additional visible particles through the same portal particle. Now there are extra visible particles in the final state, opening new search channels. Moreover, due to the existence of extra particles, you have more handles to suppress associated backgrounds. Inelastic dark matter can be realized in many particle physics models, for example, models of two real scalars and models of two chiral fermions (see Ref. [5] for detailed discussion).

There is an interesting feature of the models of inelastic dark matter. Depending on the underlying model details, the mass gap between χ and χ' can be smaller than the mass of dark photon A'. In this case, χ' cannot decay to a χ and an on-shell A', but decay to visible particles through an off-shell dark photon. Now the heavier state χ' can be long-lived, potentially showing a displaced vertex inside the LHC detectors [6]. The reason for this can be understood with the approximated expression for the χ' decay in this case:

$$\Gamma_{\chi'} \propto \alpha\alpha_D \frac{\epsilon^2(\delta m)^5}{m_{A'}^4}\,, \tag{2}$$

where α and α_D are the SM and dark-sector fine structure constants, respectively. First, since the portal scenario typically involves small coupling (here kinetic mixing parameter ϵ), the decay width is suppressed by the coupling. Second, the mass of the mediator $m_{A'}$ appearing in the propagator can be sizable. Finally, if the mass gap δm between χ' and χ is small, then the decay width will be significantly reduced. The laboratory-frame decay length is given by

$$\ell_{\chi',\mathrm{lab}} \approx 0.3\ \mathrm{mm}\left(\frac{10^{-2}}{\epsilon}\right)^2\left(\frac{0.1}{\alpha_D}\right)\left(\frac{m_{A'}}{50\ \mathrm{GeV}}\right)^4\left(\frac{5\ \mathrm{GeV}}{\delta m}\right)^5\left(\frac{\gamma_{\chi'}}{10}\right)\,, \tag{3}$$

from which we see that the decay length is sizable enough to generate a displaced vertex signature.

Recently, the authors of Ref. [7] investigated a multiple displaced-vertex signature, named “tumblers”, which would be insensitive to the existing displaced-vertex searches. A conventional displaced-vertex signal involves long-lived particles (LLPs) each of which decays to visible particles potentially together with additional invisible particles. On the other hand, in a tumbler signal, a LLP decays to another lighter LLP on and on. In other words, a sequence of displaced vertices emerge from successive decays of LLPs within the same decay chain.

Let us focus on the simplest tumbler topology, where a heavier LLP χ_2 decays to a lighter LLP χ_1 which further decays to a dark matter candidate χ_0. One remarkable kinematic feature with tumblers is that one can actually reconstruct the masses of the three resonances in the event-by-event basis, using the timing information. The mass reconstruction formulas are available in Ref. [7]. This implies that a resonance-like structure appears in the distributions of reconstructed masses. It was demonstrated that depending on the parameter region, this feature still remains even in the presence of backgrounds, finite timing resolution, and realistic detector responses. Therefore, tumblers are expected to provide unique displaced-vertex search channels.

In principle, tumblers can arise in whatever new physics models containing multiple long-lived particles, including extended dark-sector scenarios with mediator-induced decay chains [8] that are defined as follows:

$$\mathcal{L}_{\rm int} = \sum_q \sum_{n=0}^{2} (c_{nq}\phi_q^\dagger \bar{\chi}_n P_R q + h.c)\,. \tag{4}$$

Basically, the SM quarks are interacting with new particles, and $\chi_{2,1,0}$ are SM-singlet Dirac fermions. χ particles and quarks are interacting through the mediator ϕ which is assumed to be a color-triplet and constructed as to suppress any flavor-changing effects. Finally, each χ couples to ϕ with coupling c_n obeying the scaling relation $c_n/c_0 = (m_n/m_0)^\gamma$ with γ being a scaling parameter.

Assuming that ϕ is the heaviest new particle, the model basically tells that χ_2 and χ_1 decay to lighter states through a virtual ϕ. Therefore, tumblers can arise when χ_2 is produced at the primary vertex and decays to χ_1 which subsequently decays to χ_0. Partial decay widths of χ particles scale like coupling parameter quartic, so if c_n is sufficiently smaller than 1, both χ_2 and χ_1 are likely to be long-lived, hence successive displaced vertices can arise. Indeed, this kind of behavior is not specific to this particular model. If a given dark sector contains multiple dark-sector species that weakly couple to the portal particle, then the existence of multiple long-lived particles is natural, and therefore, it is likely to have tumbler-like signatures at the LHC once a heavier dark-sector state is produced.

3. Conclusion

Dark-sector portals can allow for systematic progress in understanding dark-sector physics including dark matter. LHC can provide various physics opportunities in the search for dark-sector portal scenarios. In particular, non-minimal dark-sector scenarios can provide promising search channels at the LHC that are not yet investigated. Two example cases were discussed here. First, models of inelastic dark matter allow for rich LHC phenomenology including multiple final-state visible particles and displaced vertex signature. Second, multiple sequential displaced vertices are a novel signature and allow for resonance-like mass reconstruction of new particles in combination with upgraded timing modules of the LHC detectors.

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